GALILEO SATELLITE TOUR: ORBIT DETERMINATION

R.J. Haw, P.H. Kallemeyn, F.T. Nicholson, R.P. Davis, J. It. Riedel*

This paper discusses orbit determination results for the Galileo satellite. tour I. 1 acking a high gain antenna, the mission will use a low gain antenna for communication and tracking. This change implies far less navigation data will be available than previously expected. A baseline orbit analysis was completed assuming this decreased data schedule. Variations on this baseline were studied to determine sensitivity to data loss. Results indicate that the probability of completing the tour is less than 90%, although future improvements in orbit determination promise to raise the probability of completion above 90%.

INTRODUCTION

The **Galileo** probe, which will explore the Jovian system, logically succeeds the early reconnaissance missions of the Pioneers, the Voyagers, and Ulysses. 7'110SC spacecraft flew past Jupiter, spending little time in its system. Galileo differs from them in that it will remain within the Jovian system, studying the planet, its magneto - sphere, and its four major satellites for a period of two years.

Insertion into orbit around Jupiter will occur on December '/, 1995 after an encounter with the satellite Io. During the following "tour", Galileo will encounter Europa, Ganymede, and Callisto at least three times each, on trajectories bringing it to altitudes between 200 and 3 10(I kilometers. The availability of precise navigation knowledge will permit flight controllers to exploit gravity-assists throughout the tour. These assists minimize propellant expenditure and enable a ten encounter tour within sixteen months.

The ten encounters occur 011 eleven orbits -- injection of an additional "phasing" orbit into the tour ameliorates mission constraints caused by a solar conjunction on January 19, 1997[1]. (An orbit is used here 10 describe the trajectory followed by the spacecraft between satellite. pericenters.) A brief overview of tour characteristics is presented in Table 1[1]. In the tour so called non-targetted encounters are also objects of study. Non-targetted encounters have higher altitude flybys and therefore don't contribute significantly to trajectory gravity-assists. These are listed in Table 1 as well, but have an " N " suffixed to the encounter number and appear in smaller size font.

The Jovian satellite tour was originally designed to return high rate science and navigation information. En route to Jupiter, however, Galileo's deployable high gain antenna (HGA) failed to open, leaving a single low gain antenna (LGA) as the spacecraft's sole, telecommunication link. The tour described in Table 1, though optimized for an HGA mission, will nevertheless remain for the LGA mission.

* Navigation Systems, Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA 91109

Table 1
GA1 JLEO SATEI,1,1"1'11 TOUR CHARACTERISTICS

Encounter	Sate. llite	Date	Pre-encounter Period (clays)	Altitude. (km)	True Anomaly · (degrees)
G1	Ganymede	July 4 '96	>30	500	-6?
G2	Ganymede	Sept. 6 '96	63	?00	-68
C3	Callisto	Nov. 4 '96	58	1096	-113
E3N	Europa	Nov. 6'96		31,800	29
E4	Europa	Dec. 19 '96	44	695	23
E5N	Europa	Jan. 20'97		27,600"	5
E6	Europa	l'et). ?() '9"/	30	589	-24
E7N	Europa	April 4 '97		25,000	-?9
G7	Ganymede	April S '9-/	43	3105	84
C8N	Callisto	May 6 '97		33,200	-120
G8	Ganymede	May 7 '9-1	31	1602	-84
C9	Callisto	June 25 '97	48	4?0	-111
G9N	Ganymede	June 26 '97		W),?(UI	-68
C10	Callisto	Sept. 17 '9"/	83	528	-111
E11	Eutopa	Nov. 6 '97	49	1127	-18

This paper assessess the orbit determination (OD) capabilities of the LGA mission. Despite significantly degraded navigation data, it concludes that the potential for completing the LGA (our remains high.

1 DESCRIPTION OF PROBLEM

Propellant margin (I'M), the mass of fuel and oxidizer remaining after ten encounters, is a concern to flight controllers. Positive PM indicates a 90% probability of tour completion, whereas negative PM implies a probability of less than 90%. Nearly 9-/% of Galileo's propellant is expended before the tour starts (thirty days before the first encounter, m G1 minus 30) so I'M, as a major driver in the tour, is closely monitored and continually re-assessed to ascertain the liklihood of completing the tour'. Ten encounters are assured only if propellant usage is modest -- and guiding the spacecraft with a minimum of thrusting requires accurate orbit determination.

The need for accurate OD raises concerns about navigating the LGA tour, with its dearth of navigation data and the lack of redundancy therein implied. The HGA mission had X-band data rate capabilities of] 15,000 bits per second (bps) -- ample bandwidth for navigation measurements. The LGA mission is expected to return, at best, only 160 bps over 2.29 GHz S-band frequencies, with a mean rate of 40 bps [2]. We expect to acquire two- way coherent doppler data, but no timing (range) data. (Range, which requires precise point- to- point measurements, has a unfavorable signal-to-noise ratio and is unusable, whereas doppler, formed by integrating range measurements over time, is practicable.) So in the end, the paucity of the LGA telecommunications rate and the priority of science data conspire 10 limit the. acquisition of navigation data.

Optical navigation images (opnavs) *i.e.* satellite images against a stellar background, are a pillar of the LGA tour. Opnavs ascertain satellite-relative position information. Satellite images, shuttered with the on-board imaging system, become very valuable to navigation because of the satellite-relative information they provide *prior* to the encounter. Conversely radiometric measurements, providing only barycentric information, cannot improve the satellite ephemeris (although doppler does supply useful time-of-flight information). Thus a campaign of opnav imaging conducted over some judicious interval before the encounter will reduce, perhaps substantial] y, the *a priori* ephemeris uncertainty and thereby minimize delivery dispersions.

Herein lies the crux of another difficulty with the LGA tour. Transmitting a single opnav over the low gain antenna le.quilts a~)~)lc)xili-late.ly six hours of dedicated downlink, a long interval for even a single opnav, much less an entire opnav campaign given the. mission's other priorities *(e.g.* returning science data). Yet the tour remains unnavigable without opnav data (shown later in the paper).

In the following sections several schemes are discussed to navigate Galileo through the Jovian tour via a low gain antenna.

FILTER MODEL

Each orbit is treated independently in the analysis, but for purposes of continuity some overlap between orbits is desirable. Thus the spacecraft trajectory for orbit *i* was integrated from an epoch state located five days before encounter i-1, and ended shortly after encounter *i*. "l'ire. integration modelled ail known significant dynamic forces acting on the spacecraft, and employed JPL planetary and Jovian satellite ephemerides [3,4].

During each orbit, three principle propulsive maneuvers called orbit trim maneuvers (OTMs) occur. The place.mc.llt of the first and third of these maneuvers is similar to previous studies [5]. The maneuvers are described below.

The first maneuver, labelled U1'A41, is performed three days after encounter *i-1* (excluding orbit 1). This post-encounter maneuver is required for statistical reasons. We anticipate an adjustment to the actual spacecraft velocity (a Av not included in the nominal trajectory) in order to correct maneuver and trajectory errors at the just-completed encounter. CY1'h41 will perform this clean-up. OTM2 is located in the middle of the. data arc, at Jovian apocenter, between encounters *i-1* and *i* (again excluding orbit 1). This maneuver, partly deterministic *(i.e.* included in the design trajectory) targets to the encounter *i* aim point assuming a nominal swingby of the previous encounter. OTM3 (another statistical maneuver) is positioned three days before encounter *i*. Its purpose is to re-target Galileo to the desired aim point, correcting previous OD errors anti OTM2 deficiencies.

Orbit determination covariances were computed with epoch state, least-squares, square root information filters [6,7,8]. These covariances are mapped forward with State transition matrices to a time of interest (the close.st approach 10 the satellite) and transformed into target-centered B-plane coordinates (see reference [9] for a discussion of the H-plane coordinate system). Mapped covariances indicate the magnitude of the 10 OD dispersions we expect to set during the tour. (Within a 1σ ellipse will fall 40% of all encounter trajectories.)

Inputs to the. filter consisted of the *a priori* uncertainties in the model parameters, and are listed in Table 2. Estimated parameters included (reference cite.s source of the

Table 2
A PRIORI UNCERTAINTIES IN THE MODEL,

ESTIMATED PARAMETERS

Parameter	Uncertainty (1σ)	Comments
Spacecraft initial position	10^4 kill	
Spacecraft initial velocity	100 m/sec	
OTM velocity impulse (Av)	1.2% of total Av	
Attitude maneuver Av	2 mm/sec	2 per month, & ±1 day from enc.
Camera pointing & orientation		
α, δ	2 millirad	estimated for each opnav
Twist around optical axis	35 millirad	estimated for each opnav
Satellite ephemeris		
Europa		
Orbit Orientation (3 Euler angles)	8 millirad	In Cartesian coordinates:
Longitude from pericenter	1 millirad	'/ km radial
Semi-major axis (As/a)	'/ parts in 10^6	43 km alongtrack
Eccentricity (Ae/e)	1 part in 10^3	2"/ km out-of f-plane
Ganymede		
Orbit orientation (3 Euler angles)	1? millirad	In Cartesian coordinates:
Longitude from pericenter	7 millirad	10 km radial
Semi-major axis (Aa/a)	1 part in 10^6	60 km alongtrack
Eccentricity (Ae/e)	8 parts in 10^3	30 km out-of-plane
Callisto		
Orbit orientation (3 Euler angles)	S millirad	In Cartesian coordinates:
Longitude from pericenter	1 millirad	15 km radial
Semi-major axis (As/a)	1 part in 10^6	106 km alongtrack
Eccentricity (Ae/e)	1 part in 10^3	50 km out-of-plane
Jupiter ephemeris & orientation		
Orbit orientation (3 Euler angles)	2×10^{-2} millirad	In Cartesian coordinates:
Longitude from pericenter	3×10^{-4} millirad	15 km radial
Semi-major axis (As/a)	'/ parts in 10^9	150 km along track
Eccentricity (Ae/e)	2 parts in 10^7	150 km out-of- plane
Pole direction	7 X10"^{2} millirad	

CONSIDERED PARAMETERS

Parameter	Uncertainty (1σ)
DSN station locations	11 cm radial
	12 cm Z-height
	IS cm longitude
Ionosphere zenith delay	75 cm daytime
	15 cm nighttime

uncertainty): spacecraft epoch state, magnitude of orbit trim maneuvers, magnitude of attitude control impulses, camera pointing and orientation fm each opnav [10], orbital elements of the satellites [4], orbital elements of Jupiter [3], and Jupiter orientation [4].

The uncertainty in the spacecraft initial state was sufficiently large to leave it reasonably unconstrained. Uncertainties in the opnav pointing parameters -- right ascension, declination, and rotation about the line of sight (twist) -- were al] sufficiently large to leave them unconstrained too. The orbit orientation uncertainty is the mean of the root-sum-square of the. uncertainties in the three orbit Euler angles (at encounter time, since these uncertainties are periodic). Uncertainties in the ascending node and the argument of pericenter dominate this quantity.

The effect of uncertainties in model parameters about which the data was felt inadequate to estimate, but which were known to be. accurately modelled, were included through the use of consider analysis [11]. These parameters, also listed in "]'able. 2, consisted of the Deep Space. Network's fiducial station locations [12] and the calibration of the zenith delay of signals propagated through the Earth's ionosphere [13].

The c.pot}] state. (consider) covariance (Λ) computed by the filter is given by

$$\Lambda = (A^T * W * A)^{-1} + S_{xy} * \Lambda_y * S_{xy}^T$$

where A = the partial derivatives of the observables with respect to the estimated parameters, W = the weights of the data, S_{xy} = partial derivatives of the estimated parameters with respect to the considered parameters, and Λ_y = the *a priori* uncertainties in the considc.reel parameters.

Two common parameter groupings not included in Table 2 are spacecraft solar reflectivity terms and tropospheric terms affecting signal propagation. These parameters wine. indeed modelled but eliminated from the filter bc.cause of their demonstrated inconsequentiality to the OD.

Nearly the same set of parameters were estimated/considered for each orbit. The only exception lay in the number of attitude control velocity impulses estimated. Longer arcs contained more impulses.

The uncertainties associated with the tracking data were the following: for S-band two-way doppler, 1 mm/sec (averaged over 60 seconds) and for opnavs, 0.35 pixels.

DATA ARCS

Each orbit has a unique trajectory, so this analysis employs ten data sets. The data sets simulate data acquired between encounters as well as data from the latter portion of the previous orbit. Specifically, the first data point in each data set is collected five days before encounter *i-1* and the last gathered shortly after encounter *i*.

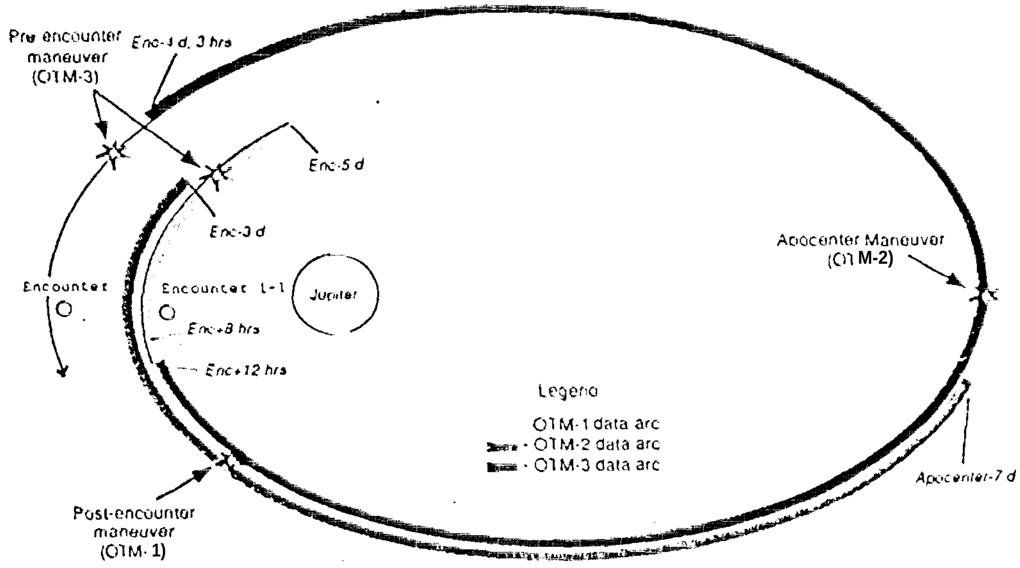

Figure 1 Representative Tour Data Arcs

Supporting each maneuver design is an appropriate subset of the data set, called a data arc. Figure 1 depicts generic data arcs for an orbit, with a detailed explanation provided below. Only maneuvers lying within data arcs are estimated in the OD.

The data arc for the design of OTM1 has a length of 5 1/3 days -- beginning 5 days bc.fore encounter *i-1* and ending 8 hours after that encounter. (Recall OTM1 executes 3 days after the. encounter.) The OTM2 data arc encompasses 12 to 39 days (variable) -- starting 3 days before encounter *i-1* anti ending 7 days before OTM2, the Jovian apocenter maneuver. 1'01 OTM3, the arc begins 12 hours after encounter *i-1* anti stretches all the way around the orbit until 4 days 3 hours before the. upcoming encounter i (equal to OTM3 minus 1 day 3 hours). Therefore this arc aiso varies in length as a function of orbit, with arc lengths spanning 27 to '/9 days.

Collecting minimal yet sufficient radiometric data to navigate the 1 .GA tour is clearly of great concern. Other studies addressed this issue anti concluded that three tracking passes per week are adequate[14]. Thus as presently formulated, tracking schedules call for three six-hour passes per week during the cruise phase between encounters. Around each encounter, continuous tracking will accumulate for 48 bouts beginning one clay before. the encounter. Only two-way coherent S-band doppler data is collected. Compare this with the HGA tour which scheduled eight eight-hour tracks per week during cruise phase and 10 days of continuous tracking around each encounter, collecting both doppler *and* range.

Overall, as an approximate figure of demerit, the information content of two-way doppler during the tour has dropped by approximately four orders of magnitude.

Optical navigation fares better. Novel image compression and editing techniques will allow the return of up to fifty opnavs per orbit (vs. two hundred in the HGA mission), a modest decrease in the total opnav information content. This opnav strategy retains the information content of each image yet returns two orders of magnitude fewer bits to the ground.

Reducing the picture budget limits the gathering of opnavs to a bimodal pattern. Most images (90%) are taken while the spacecraft is close to pericenter, with only a few images collected at apocenter (distant opnavs offer meager improvement to OD). Thus opnav data tends to cluster in the first and last weeks of each orbit.

I) IS(USS1ON

The largest *a priori* uncertanties in the analysis belong to the state of the spacecraft and the state of the Galilean satellites. Reducing these states to levels acceptable for navigation is the purpose of tour OD.

Precisely determining spacecraft location is relatively straightforward. To see this, compare the expected pre-encounter uncertainties in the spacecraft orbits of Figure 2 with the uncertainties of the Galilc-ails listed in Table 2. Just one or two months of minimal spacecraft navigation data far supercedes 300 years of Earth-based telescopic observation of the Galileans (which also includes the Voyager observations). Thus accurately locating the spacecraft is expected to be less of a problem than accurately locating the target satellite.

The *a priori* position uncertainties of Europa, Ganymede, and Callisto are also charted in Figures 3, 4, and 5[4]. Moreover, these figures illustrate a chronology of the computed position uncertainties projected to encounter time. in general as Galileo approaches a target and acquires more data, knowledge of the satellite position increases anti its root-sum-square uncertainty decreases. Especially dramatic is the decrease in uncertainties at the. times of OTM1 and OTM2 for the G? mbit. The reason for this is that the previous and upcoming encounters are both with the same

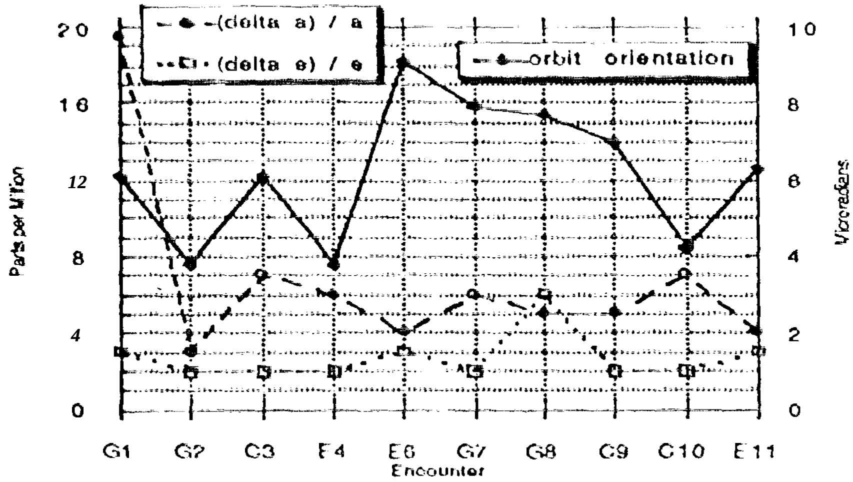

Figure 2 Pre-encounter Uncertainties in Galileo's Osculating Elements

satellite, Ganymede. The improved barycentric-relative Ganymede position obtained from the first flyby enhances the delivery to the second encounter. A similar doublet occurs again late.1 in the tour with Callisto (C9 and C1 O). The OTM l and OTM2 deliveri s for C10 should therefore also snow marked improvement vis-a-vis C9. That they do not (Figure S) is attributable to the non-targetted encounter with Ganymede in orbit 10. The Ganymede flyby perturbs the spacecraft and degrades the OD at C10. On the remaining orbits, correlations between the Galilean satellite. s due to their commensurability accounts for the modest improvement in position knowledge at OTM 1 and OTM2.

Ephemeris improvements due to flybys of previous encounters, as described in the preceding paragraph, were ignored for the pre-encounter (OTM3) sol utions. Conservatism suggested this approach, Flyby doppler data can reduce satellite position uncertainties to the sub-kilometer level (to be shown) -- a dramatic improvement in knowledge about which we did not feel comfortable incorporating into the pre-encou nter maneuver. The rational is that extrapolating the position 01 a satellite temporarily known to sub-kilometer accuracies with a theory[4] accurate to many tens of kilometers (Table 2) has been shown to be possibly unstable[15]. Thus only *a priori* satelli te covariances, not updated covariances, were applied to the pre-encounter OD analyses.

The barycentric-relative spacecraft state at data cutoff times is presented in Figure 6. Part A of the figure shows large uncertainties in spacecraft position at the time of OTM2, relative to OTM1 anti OTM3. These uncertainties are understandable in terms of geometry. in the absence of strong gravity signatures, tracking stations require long data ales to adequately locate the spacecraft in coordinate space. (Spacecraft position is a deduced quantity, not an observed value..) Most data in the. OTM2 data are is gathered far from Jupiter or satellite pericenters, leaving little in the way of a gravity signature. Furthermore, insufficient time has elapsed for the doppler to determine all components of spacecraft position to a level commensurate with a pericenter passage. Hence large uncertainties in the OTM2 column. The G8 orbit, however, stands out as an exception. Instead of degrading, position uncertainty actually improves with respect to OTM 1. This can be explained in terms of the short period of the G8 mbit. It is the briefest orbit in the tour, and consequently most of the doppler in the OTM2 data are includes a Jupiter gravity signature.

The spacecraft position uncertainties diminish dramatically for pre-encounter maneuvers. The reasons are two- fold. The radiometric data arc has doubled in length,

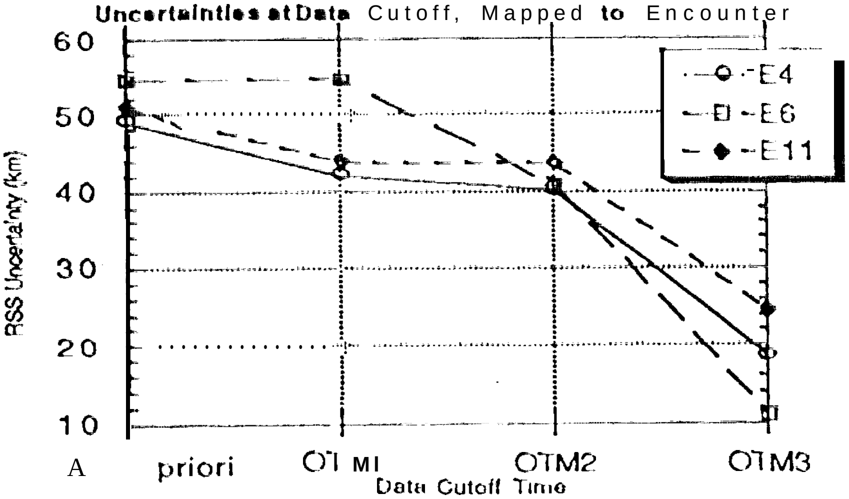

Figure 3 Europa RSS Position Uncertainties

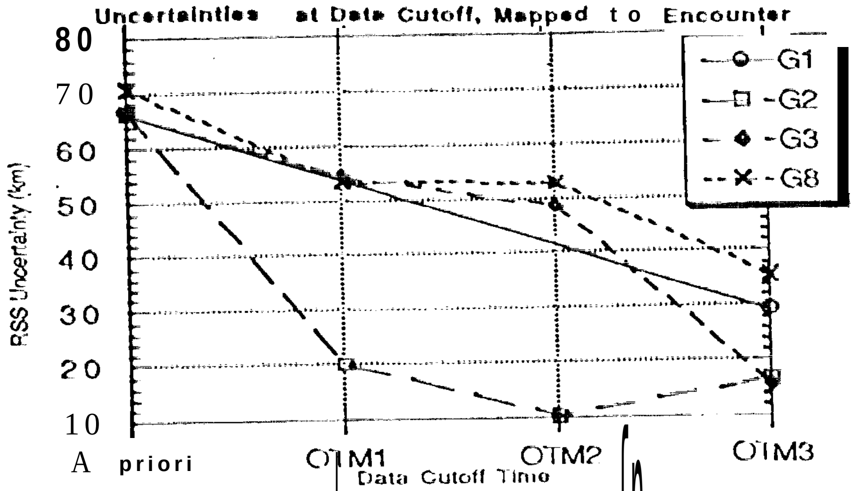

Figure 4 Ganymede RSS Position Uncertainties

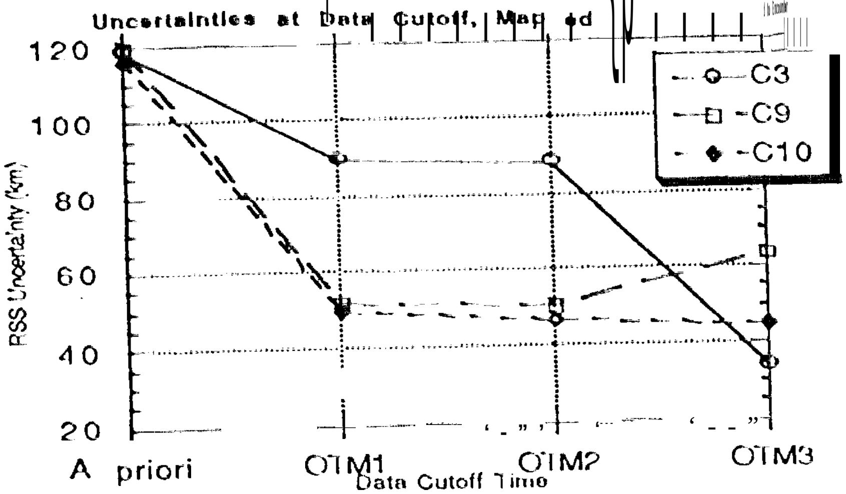

Figure 5 Callisto RSS Position Uncertainties

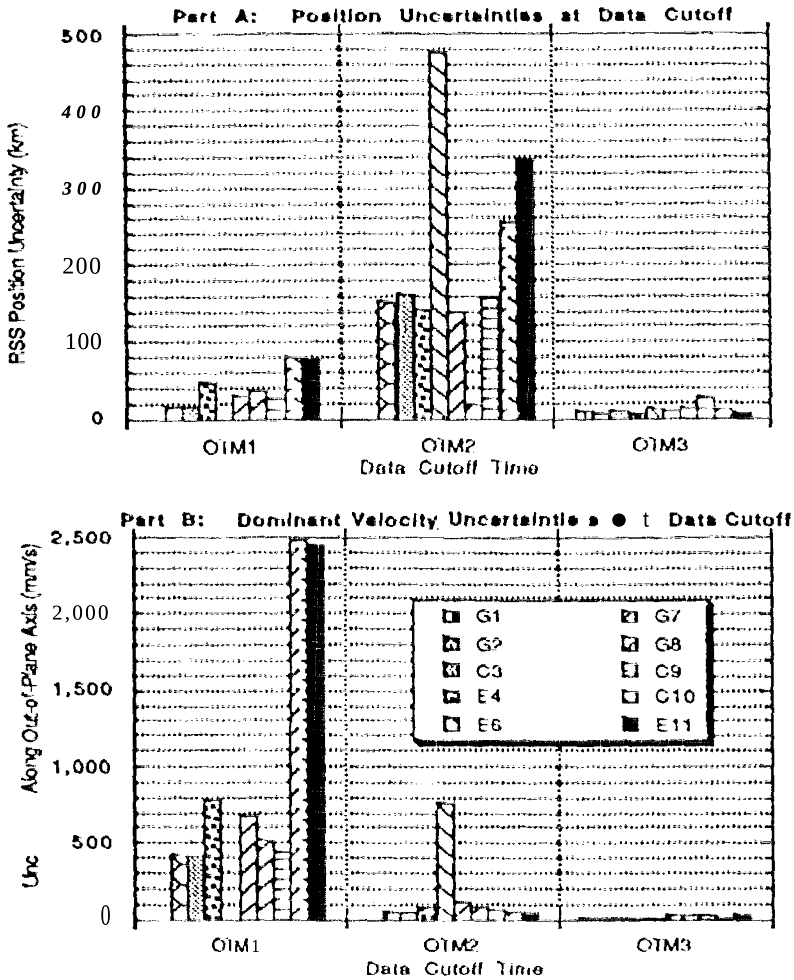

Figure 6 Barycentric Spacecraft State Uncertainties

and inclusion of opnav data has added satellite-relative position information. The satellite(s), in turn, are known with respect to the barycenter.

Figure 6B charts the dominant (not RSS) component of the barycentric-relative spacecraft velocity uncertainly at the time of maneuver data cutoffs. This graph is more intuitive than part A because of the one-to-one correspondence between data collection and reduction in velocity uncertainties. The uncertainties shrink with additional data. One apparent exception: the OTM2 uncertainty of the E6 orbit. This unusual data arc begins at Jovian apocenter and includes *no* E4 flyby data (a consequence of the solar conjunction)*. Hence the vanishing of the OTM 1 column for E6.

RESULTS

The orbit determination evaluation of the baseline LGA tour is presented in Table 3. The values therein represent B- plane uncertainties for each maneuver in the tour, as

* The conjunction data arc spans January 11, 1997 to January 29, 1997 (seven days before Jovian apocenter). The OD from this data arc is mapped to the E6 encounter. The E6 pre-encounter data arc also begins January 11, but terminates February 16 (encounter minus 4 days). Data within ±7 degrees of the Sun is excluded

TABLE 3

LGA TOUR ENCOUNTER DISPERSIONS (10)

MANEUVER	B.R (km)	B.T (km)	TOA (sec)	No. of Opnavs total (target)
G1 - 3 d	12.7	25.0	1.8	31 (14)
G1 knowledge	0.2	0.1	nil	
G1 + 3 d	98.?	3349.7	409.0	
G1,G2 apo	1.4	34.4	4.2	
G2 - 3 d	9.9	23.9	0.9	43 (18)
G2 knowledge	<0.1	0.1	nil	
G2 + 3 d	61.0	3056.1	310.0	
G2,C3 apo	43.0	79.9	4.1	
C3 - 3 d	18.6	29.5	1.3	34 (15)
C3 knowledge	<0.1	1.8	0.2	
C3 + 3 d	53.3	3125.4	1270.2	
C3,E4 apo	?1.5	21.s	6.9	
E4 - 3 d	8.4	10.3	2.5	30 (11)
E4 knowledge	1.6	0.2	0.1	
E4 + 3 d	36.5	1986.0	668.9	
phasing rev	89.4	36.0	13.4	
E6 - 3 d	11.9	10.s	0.5	29 (12)
E6 knowledge	0.1	<0.1	nil	
E6 + 3 d	41.0	400.1	5-/.4	
E6,G7 apo	38.8	47.1	3.3	
G7 - 3 d	8.0	20.6	1.7	38 (14)
G7 knowledge	<0.1	<0.1	nil	
G7 + 3 d	3].4	273.5	26.6	
G7,G8 apo	15.3	68.8	6.1	
G8 - 3 d	26.2	28.6	1.2	23 (5)
G8 knowledge	0.1	<0.1	nil	
G8 + 3 d	13.5	367.9	35.4	
G8,C9 apo	20.1	1?.4	?.0	
C9 - 3 d	34.4	53.9	2.2	26 (15)
C9 knowledge	1.7	0.3	0.1	
C9 + 3 d	33.7	1697.7	177.0	
C9,C10 apo	4.5	2?.1	2.9	
C10 - 3 d	20.7	3?.7	1.8	39 (13)
C10 knowledge	1.7	0.2	nil	
C10 + 3 d	249.7	125.2	57.8	
C10,E11 apo	43.0	17.7	6.5	
E11 - 3 d	9.6	6.9	2.5	47 (18)
E11 knowledge	0.7	0.8	0.1	

well as the expected errors in the time of arrival at the B-plane (TOA). The rows labelled "knowledge" list *a posteriori* uncertainty in the achieved flyby point *i.e.* the uncertainty in the position of the spacecraft at closest approach computed using pre- and post-encounter data. The row labelled "phasing rev" between E4 and E6 denotes the solar conjunction orbit, where no targetted encounter is planned.

The numbers of opnavs shuttered for each encounter are listed in the rightmost column of Table 3. The total number of opnavs (all satellites) is provided thin, as wc]] as the number of opnavs of the target satellite.

Remarkably, Galileo navigators can accept much of the LGA OD. Despite losing a significant fraction of the data originally intended for navigation purposes, in general the tour remains navigable with the low gain ante.n[]n. Some exceptions exist, how-ever, and three deliveries in particular substantially degrade PM [16]. Not surprisingly, these represent the pre-encounter deliveries to the three lowest altitude targets in the tour (Ci 1, G2, and C9).

The C9 pre-encounter delivery stands out as especially anomolous (*B.R* = 34 km, *B.T* = 54 km, and *TOA* = 2.? see) and deserves special comment. The large Callisto *a priori* uncertainty manifests itself in this encounter, yet it is conspicuous even with respect to comparable flybys (*i.e.* C3 and C10). An explanation can be found in the spacecraft trajectory. The G8-C9 orbit has the shortest period of the three Callisto encounters, and less data implies a poorer determination of the orbit. Figure 2 confirms that C9 has large uncertainties in orbit orientation (verified by the. OTM3 column of Figure 6A). From Figure S one sees that the computed Callisto uncertainty has remained relatively high too, also a consequence of the briefer C9 data arc.

Sensitivity to Data Loss

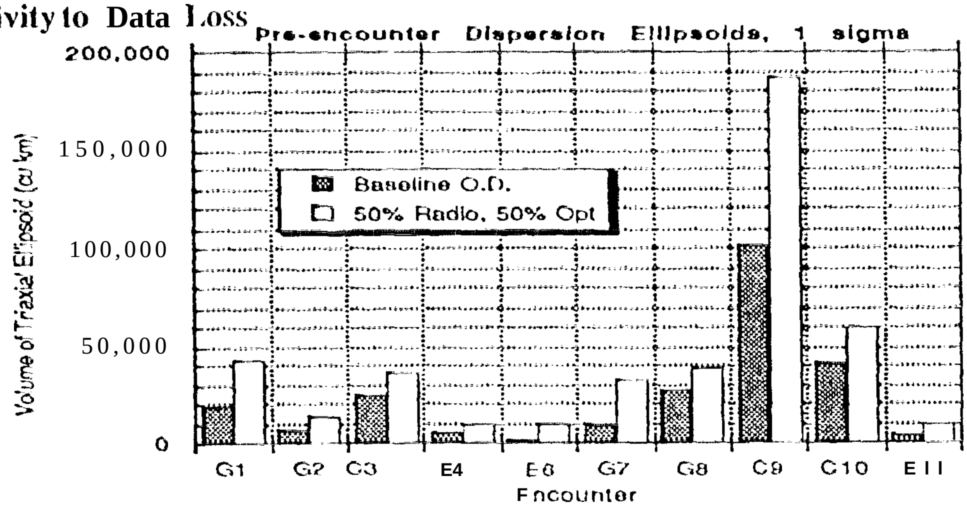

Figure 7 Sensitivity to Data Loss

The sensitivity of [our OD to data loss was investigated. The impact on the tour by reducing radiometric and opnav data densities by a factor of two is shown in Figure 7. The ordinate in Figure 7 measures volume of the encounter dispersion ellipsoid, equal to the product of (4/3)π with uncertainties in B-plane semi-major axis, semi-minor axis, and downtrack axis. Very approximately, the figure shows an inverse relation between navigation] data and delivery dispersions. Acquiring half the data will, roughly, double the dispersion ellipsoid.

Trials sensitive to losing specific data types were also examined. The first trial determined sensitivity to range by *adding* range data to the baseline case. Results, however, were indistinguishable from baseline rc.suits, so range data appears to have limited applicability to the LGA tour.

A second trial examined sensitivity to interferometric measurements [17]. At a rate of two so-called delta-differential one-way range points per week. the results again were indistinguishable. from base.line results. Thus interferometric data has limited utility for the LGA tour.

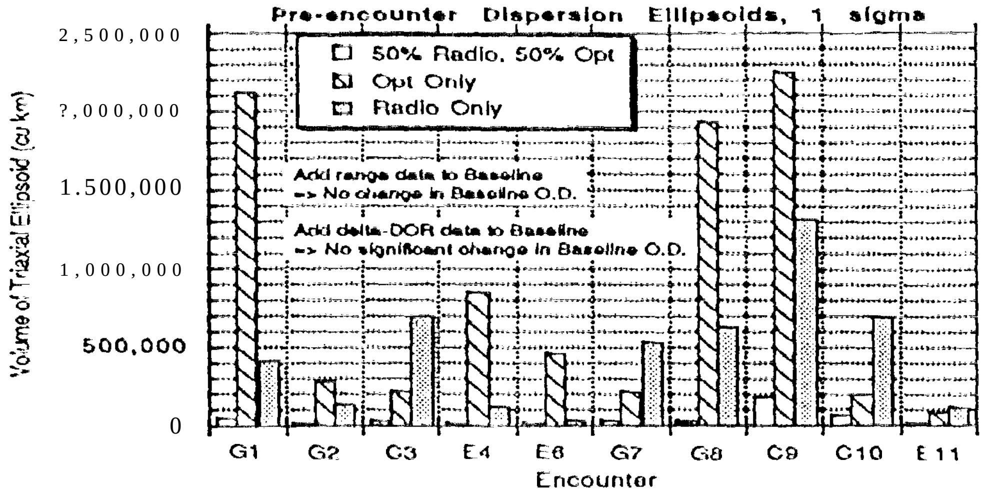

Figure 8 Sensitivity to Data Ty pe

Sensitivity to the 10ss of either doppler or optical measurements is more sever e. Figure 8 illustrates these trials. Successfully completing the tour is impossible without both doppler and optical data. The time-of-flight error induced by the loss of doppler data is not compensated for with opnav-only navigation, anti the loss of barycentric-relative satellite data (opnavs) highl y degrades the doppler-onl y rc.suits. But a combination of these data types, even with only a 50% success rate, produces results far superior than a full schedule of just a single data type.

Propellant Margin Status

Currently (August 1 6, 1 993) PM approximately equals -10 kg. At this level, the baseline case has roughly even odds of completing the tour. The tour itself consumes approximately 58 kg of propellant (Av = 110 m/see). Of this total, the. post-encounter maneuvers G], G2, slid C9 alone consume 26 kg of PM[16]. (The propellant consum ption of post-encounter maneuvers is significantly influenced by pre-encounter OD.) The performance of only a few maneuvers has reduced expectation for completing the tour beneath the 90% threshold.

FUTURE IMPROVEMENTS

Prospects for concluding the tour appeal less than certain judging by the results described above. Little margin exists in the data schedule for possible (and probable) telemetry loss, so losing navigation data will further handicap the mission. Although losing a modest fraction of doppler data (much less than half) will have little or no affect, losing more than 10% or 15% of the opnav budget will seriously degrade the OD. This loss becomes especially poignant if *target* satellite images fail. In the G8 orbit only five images of Ganymede are shutte.red, all within the last day of the data arc. Each opnav contributes vital information to the OD, so losing even a single image inflates cie.lively dispersions. For example, excluding all five Ganymede images ft om the G8 pre-encounter data arc increases dispersions to the following val ues: *B.R* = 1 1 0 km, *B.T* = 69 km, and *TOA* = 2.3 sec. Pre-encounter statistics of this magnitude immediately doom the remainder of the tour. How then, to improve the prospects for a 10090 completed mission?

Two possible sources of 01) improvement present themselves in Figure 9. One method processes ail *flyby* data from encounter *i-1* in the pre-encounter data arc of orbit *i* (*i.e.* the pre-encounter data arc star ts 3 days before *i*- 1). This method

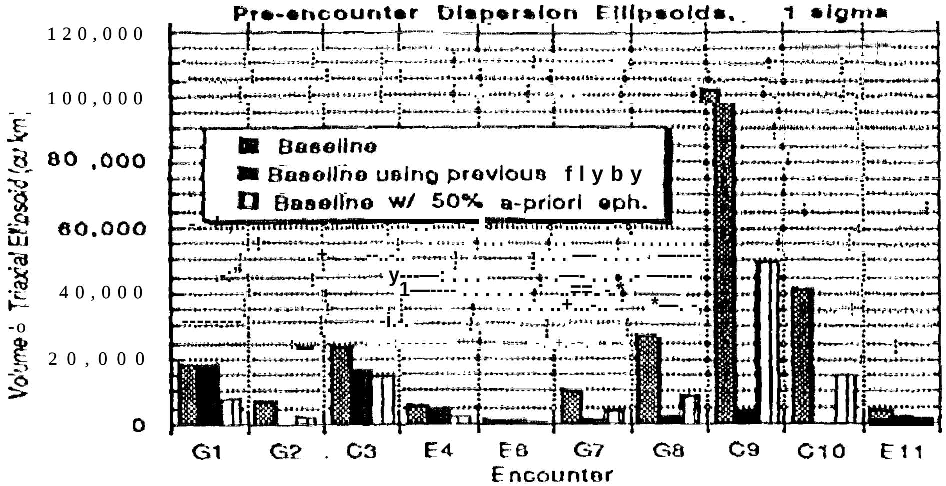

Figure 9 Sensitivity to **Potential OD improvements**

practically eliminates B-plane. errors. Swinging by encounter' i-] gene. rate.s copious doppler data and the knowledge gained, either directly or indirectly through Galilean correlations, reduces the *a priori* ephemeris uncertainty at encounter *i*. As note.cl, however, some reservations exist regarding the robustness of this approach.

Since the covariance of a planet or satellite depends largely upon the observations to which the ephemeris is adjusted, an alternate program for OD improvement has the goal of improving the *a priori* ephemeris *before* the spacecraft's arrival at Jupiter [18]. 'l'his ground-based observing program proposes to reduce *a priori* uncertainties by a factor of two, with the expectation that improved knowledge of the ephemeris will benefit PM, Figure 9 suggests the OD improvments possible with a 50% smaller covariance. Translated into PM, the savings from halving the covariance will increase. PM by 61/2 kilograms [19]. This quantity of propellant roughly equates to adding an additional encounter to the tour.

Another option is to re-position inane.uvers. Moving the C9 pre-encounter maneuver from encounter minus 3 days to encounter minus 2 days adds an extra day of data. Ultimately, the ensuing improvment to OD reduces the C9 dispersion ellipsoid to a volume equivalent to that of G 1, a colossal improvement [20]. 'l'his single change increases PM by 5½ kilograms [21].

CONCLUSION

Orbit determination of an LGA mission has degraded with respect to the OD originally envisioned for the HGA tour. But by combining new and reduced *a priori* satellite ephemerides with flexibility in positioning orbit trim maneuvers, a covariance analysis clearly suggests that an LGA Galileo will successfully navigate. ten Satellite encounters. "1'bus, although the telecommunications bit rate dropped four orders of magnitude with the loss of the HGA, visiting the Galilean satellites remains an achievable objective for Galileo. As shown, however, a non-trivial deficiency remaining in the LGA mission is the lack of data redundancy anti overlap. Little margin exists for 10ss of navigation data.

AKNOWLEDGEMENT

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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